Blood pressure monitoring: Sharing common elements, problems

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Intensive care units (ICU) have spread widely in the last 20 years and as a consequence so has blood pressure monitoring. Since it is not currently possible to monitor pulmonary artery or wedge pressure indirectly or noninvasively and since for critically ill patients the "cuff" measurement of arterial pressure is often inaccurate or impossible to determine, the direct measurement of these pressures are common in the modern ICU.

With the introduction of the balloon flotation catheter (Swan-Ganz), measurement of pulmonary artery and wedge pressures as well as cardiac output has become a widely used clinical tool. Direct arterial pressure measurements through catheters placed in peripheral arteries has also become widely used. The pulmonary and arterial pressure monitoring systems share common elements: a plumbing system — a catheter, extension tubing, stopcocks, continuous flush device and a transducer; and an amplifier-display system — a transducer amplifier, oscilloscope or strip chart recorder (Figure 1). The plumbing system used can often distort the actual pressure signal because it has characteristics of a second-order linear dynamic system — most often underdamped.

10 problem areas exist

The direct measurement of arterial and pulmonary artery pressures share many of the same dynamic response-limiting problem areas. Figure 1 outlines 10 problem areas for an arterial monitoring system. Except for the first (artery) area, the problem considerations are the same for direct arterial and pulmonary artery pressure measurements. To help the bioengineer better understand the 10 problem areas, each will be discussed briefly.

EDITOR'S NOTE: We asked Dr. Gardner to write about a topic that he has been studying for much of his career. The article that follows is tutorial in nature but for good purpose. While all biomedical engineers are aware of the damping characteristics of catheter-manometer systems, far more often than we'd care to recount, in actual practice highly distorted and often misleading waveforms are present in the critical care unit. Dr. Gardner's summary of the factors affecting the system should help clinically-associated people tend to these corrections.

1A. Arterial Pressure (artery) — Measurement of arterial pressure at the radial or other peripheral artery can give pressures which are quite different from those measured in a central artery such as the aorta or subclavian artery. When only a short (5-7 cm) catheter is inserted into the radial artery, the radial and brachial arteries are used as "catheter extensions" to measure the central arterial pressure. Since these arteries change their tone (size and stiffness) especially in the critically ill patient, clinical error can be made if a central arterial catheter is not in place. The arterial bed between the radial artery can also be characterized as a second order linear dy-

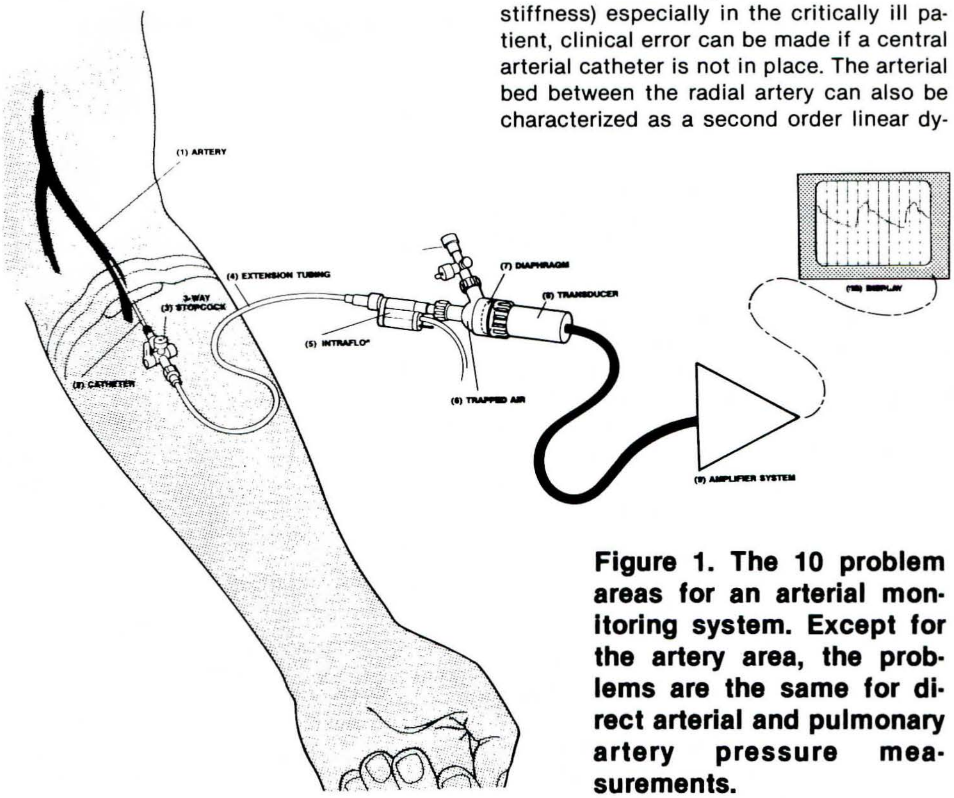

Figure 1. The 10 problem areas for an arterial monitoring system. Except for the artery area, the problems are the same for direct arterial and pulmonary artery pressure measurements.

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namic system with a low natural frequency (f_n4-7 Hz) and a changing damping coefficient.

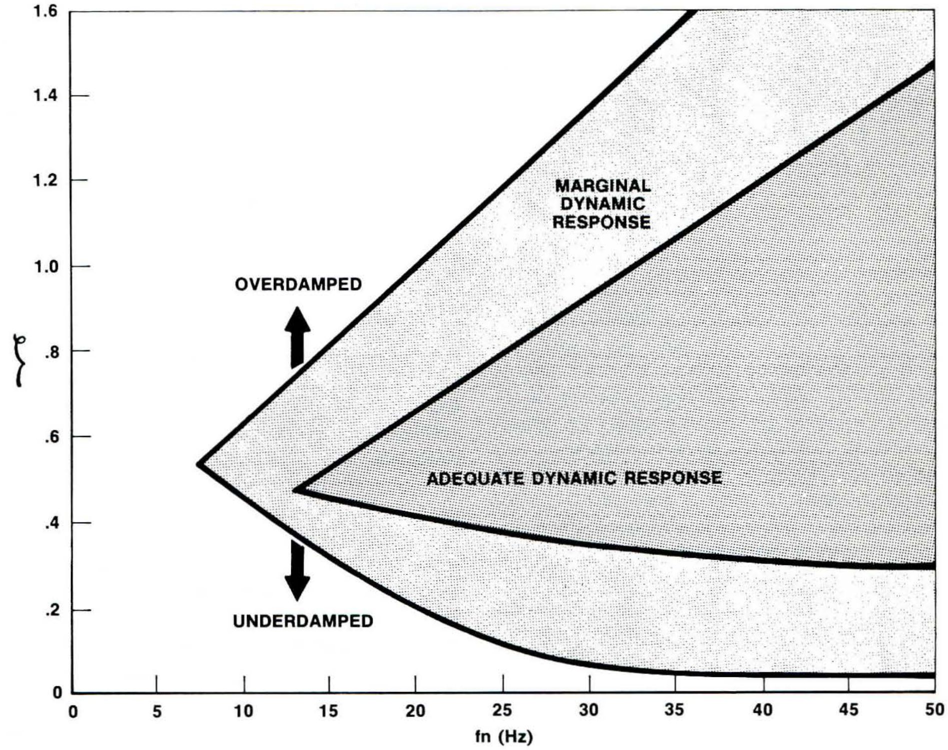
To illustrate the effects the vascular extension has on these measurements, two examples are given: normal subjects will have radial arterial systolic pressures which are 10-20 mmHg greater than those measured in the aorta while diastolic pressures are about the same. For patients in shock with peripheral vaso-construction and hypotension, the radial arterial pressure will usually look "damped." Radial systolic and diastolic pressures can be in "error" by as much as 10-30 mmHg. It is likely that the same phenomenon limits the accuracy of indirect blood pressure measurement techniques for a patient in shock.

1B. Pulmonary Artery Pressure (catheter whip) — Because the Swan-Ganz catheter goes through two valves and also moves freely in the right ventricle, mechanical artifacts are coupled into the pressure monitoring system. These artifacts are amplified by most plumbing systems.

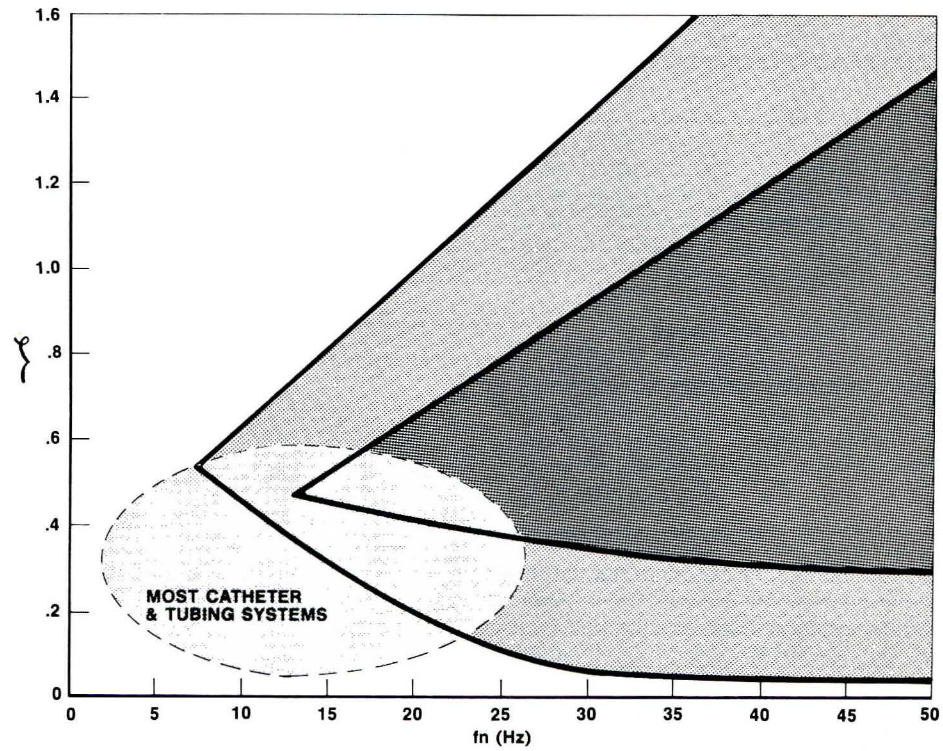
Dynamic Response Needs — Several techniques which characterize the dynamic response of catheter-transducer systems have been proposed. However, we found that none looked critically at how the clinically measurable second-order dynamic parameters natural frequency (f_n) and damping coefficient (ζ) interact to determine the fidelity.

To explore this issue two patients' waveforms were selected from patient data tapes. (Patient waveforms vary because of heart rate, pulse pressure and other physiological variables.) These waveforms were then processed through a catheter-extension tubing simulator where fn and could be selected. Input and output waveforms were recorded, and the output waveform distortion was carefully inspected visually. For the first patient (typical) a minimum natural frequency of about 7 Hz was required, if a damping coefficient of about 0.55 was in effect. For the same patient, if the natural frequency is 20 Hz, the range of damping coefficient can go from about 0.2 to 1.0 and still have adequate fidelity (left wedge) (Figure 2).

For the second patient, the limits were even tighter (right wedge). These results show that to ensure adequate response for recorded waveforms, the higher the natural frequency, the broader the acceptable range of damping coefficient. Thus, one



Figures 2 and 3. Comparison of two patients' waveforms.



cannot look at either natural frequency or damping coefficient alone to establish adequacy of dynamic response. Figure 2 shows the regions where adequate and marginal response can be obtained for catheter-transducer systems. As can be seen, most catheter tubing systems fall outside the optimal region and some are even outside the marginal response area.

2. Catheter — The catheter is usually the limiting element in determining the fidelity of the plumbing system. Geddes has developed a model which approximates the dynamic characteristics of a catheter-transducer system:

$$f_n = \frac{1.4 \times 10^3\ d}{\sqrt{V_d \times L}}\ \text{Hz} \qquad (1)$$

$$\zeta = \frac{1.36 \times 10^{-5}}{d^3} \sqrt{V_d \times L} \qquad (2)$$

where the catheter is filled with normal saline and

d = catheter diameter (cm)
L = catheter length (cm)
V_d = volume displacement of the transducer (mm^3/100 mmHg (for the best transducers about 0.01 mm^3/100 mmHg)

From these equations it is apparent that a short (small L) large diameter (large d) catheter would give the highest natural frequency which is the most commonly used measure of fidelity. However, in the clinical situation opposing considerations exist. To minimize major complications such as thrombosis formation, the smaller the catheter relative to the artery diameter, the lower the risk — a small diameter catheter is desired. To reach the pulmonary artery or the aorta requires a catheter of reasonable length (about one meter). Therefore, the medical requirements will usually prevail and challenge the bioengineering and nursing staff to maintain an **optimum** system.

3. Stopcocks — Any element in the plumbing system which can trap air bubbles or is "elastic" (increased V_d) adds capacitance and decreases the fidelity of the system. Generally, pressure monitoring systems that have a minimum of stopcocks, tubing and other interconnections give higher fidelity waveforms.

4. Extension Tubing — Many hospitals use extension tubing of varying lengths to connect catheters to transducers. This tubing should be noncompliant and as short as is practical. Table 1 gives the volume displacement of various brands, materials and models of extension tubing. As can be seen from Equation 1, the smaller the volume displacement, the better the fidelity. Table 2 summarizes the natural frequency and damping coefficient of six feet of tubing alone (direct) and the tubing with a Swan-Ganz catheter connected. Note than in every case, a dramatic decrease in natural frequency occurs when the Swan-Ganz is connected.

TABLE 1 Volume Displacement of Extension Tubing (6 foot lengths)

	Brand	Model	Internal Diameter .001 inches	Volume Displacement mm^3/100mmHg $\frac{\Delta V}{\Delta P}$	Material
1	Cook	1DPT5.3180MYF	36	1.6	Polyethylene
2	Medex	MXX666	45	1.7	Polyethylene
3	Cobe	41-066	46	1.8	Polyethylene
4	Sorenson	PT-72	49	6.4	PVC
5	Pharmaseal	—	60	11.3	PVC
6	Medex	MX566	64	13.4	PVC
7	Namic	1722	64	9.6	PVC
8	Medex	MY546-R	65	17.1	PVC
9	Cook	IDPT9.5180MYF	68	4.2	Polyethylene
10	Cobe	40-106	70	2.8	Polyethylene
11	Medex	MX466	75	3.6	Polyethylene
12	Marcel	"Arterial Line"	80	15.0	PVC
13	Urethane	—	79	7.2	Urethane
14	Abbott	Venotube	—	83.0	PVC

TABLE 2 Dynamic Response — Extension Tubing Effect
Direct = Tubing only 6Fr SG = 6 French Swan-Ganz catheter attached to tubing

		Natural Frequency f_n (Hz)		Damping Coefficient ζ	
	Brand	Direct	6Fr SG	Direct	6Fr SG
1	Cook	28	14	0.14	0.17
2	Medex	28	18	0.12	0.18
3	Cobe	28	17	0.13	0.17
4	Sorenson	29	12	0.22	0.20
5	Pharmaseal	29	14	0.10	0.21
6	Medex	25	11	0.24	0.30
7	Namic	32	11	0.10	0.22
8	Medex	21	12	0.14	0.33
9	Cook	37	15	0.06	0.14
10	Cobe	38	9	0.10	0.25
11	Medex	26	15	0.10	0.18
12	Marcel	25	11	0.07	0.30
13	Urethane	overdamped			
14	Venotube	overdamped			

(See Table 1 for tubing description)

5. Continuous Flush Device (Intraflo) — The continuous flush device, a single use device, provides for a 1-3 ml/hour flow of normal saline and prevents the catheter from clotting. Any compliant components of this device will cause a reduction in system fidelity. Since the flush device is normally near the transducer its volume displacement will be in parallel with the transducer (see Equations 1 and 2). Some flush devices on the marketplace have volume displacements an order of magnitude greater than the transducer.

Most continuous flush devices also have a fast flush capacity which allows the clinical user to test the system's dynamic response characteristics. By opening the fast flush valve and letting it close quickly a square wave excitation is applied to the plumbing system. By recording the response, the natural frequency and damping coefficient can be easily measured. Some flush devices do not have a rapid closure and thus don't allow for this test method.

6. Trapped Air — Trapped air in the system is the major operational problem when setting up a pressure monitoring system. Great care should be used when initially filling and setting up a monitoring system. Since air has a large volume displacement (equation 1 and 2), its detrimental effect on the system is dramatic even for small air bubbles.

7.Diaphragm — Disposable diaphragm domes for pressure transducers have come into widespread use in the past few years. They are convenient to use because the transducer need not be sterilized between uses. There are, however, some problems caused by diaphragm domes. Static pressure errors occur if the diaphragm dome does not come into intimate contact with the transducer diaphragm. For a transducer system calibrated to read 100 mmHg, when that pressure is applied through a non-diaphragm dome, placing a diaphragm dome on and again applying the 100 torr pressure may only give an output of 90 mmHg.

Also, dynamic pressure errors can occur. If the diaphragm dome is not perfectly coupled with the transducer diaphragm, there can be waveform distortion. Air bubbles between the plastic membrane and the transducer are a major problem.

8. Transducers — Most transducers on the market today are adequate. However, the range of volume displacement for available transducers is large (0.01 to 0.2 mm^3/100 mmHg). Also some transducers specify 0.04 mm^3/100 mmHg when they are actually 0.2 mm^3/100 mmHg. Therefore, since volume displacement of the system is so important (equations 1 and 2), the user should be aware of this potential limitation.

9. Amplifier System — Many amplifiers in commercially available monitors have adequate frequency response to reproduce pressure waveforms. Systems with frequency responses of DC to 50 Hz are generally adequate for amplification of pressure signals. Problems with frequency response with some monitor amplifiers result from a current trend to limit the system bandwidth to 12 Hz or less to compensate for the underdamped plumbing system. By limiting the frequency response with such methods the clinical user is unable to measure and optimize the f_n and of the plumbing system.

10. Display — Oscilloscope displays are usually no problem for dynamic response measurements, but paper recorders without adequate dynamic characteristics can be a problem.

Optimum dynamic response is required if systolic and diastolic pressures are to be accurately measured. If mean pressure is the only measurement required, then dynamic response characteristics are of little importance. With increasing use of derived variables, such as rate-pressure product, it is even more important that correct pressures be measured.

A system with inadequate dynamic response, whether underdamped or overdamped, will result in an error in the measured systolic pressure. The systolic pressure from an underdamped system will be overestimated, and the systolic pressure from an overdamped system will be underestimated. Diastolic pressure also is affected, but it is much more tolerant of dynamic response inadequacies. If invasive pressure monitoring systems are used, with their attendant risk of complication to the patient, great care should be taken to obtain accurate and reliable data. Simply looking at the waveform does not provide sufficient information for one to determine the adequacy of dynamic response. □

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